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INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(51) International Patent Classification [5] : G09G 3/22, 3/28

A1

(11) International Publication Number: WO 95/20811

(43) International Publication Date: 3 August 1995 (03.08.95)

(21) International Application Number: PCT/US95/00581

(22) International Filing Date: 12 January 1995 (12.01.95)

(30) Priority Data:
189,418 31 January 1994 (31.01.94) US

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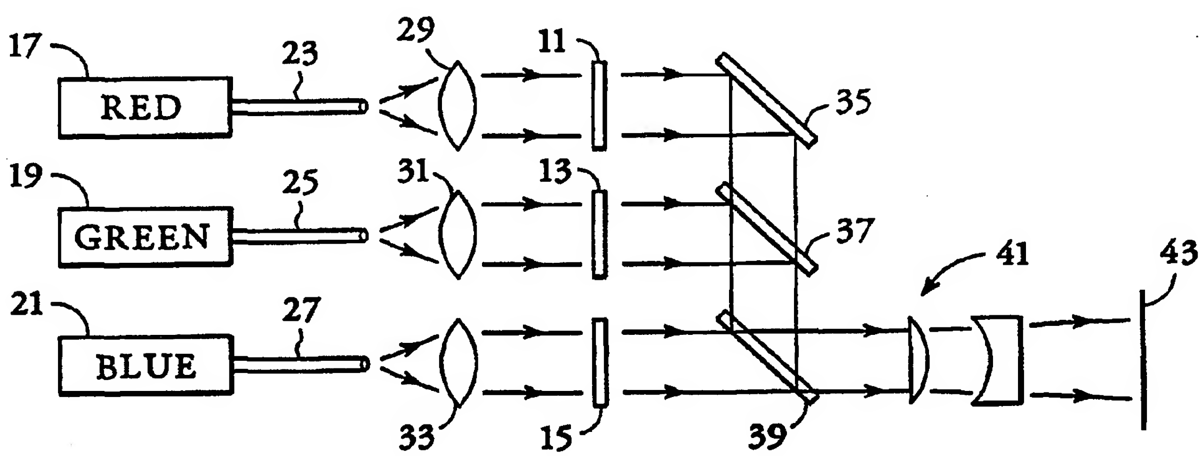
(81) Designated States: JP, European patent (AT, BE, CH, DE, DK, ES, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE).

Published
With international search report.

(54) Title: LASER ILLUMINATED DISPLAY SYSTEM



(57) Abstract

A display system in which lasers scanlessly illuminate the pixels of a spatially modulating display panel (11, 13, 15), such as a liquid crystal display or micromirror array. At least three sources at least one of which is a laser with each different wavelengths are used, such as laser diode-based sources (81, 83, 85) producing red, green and blue light. The laser may be pulsed rapidly in sequence to provide time multiplexed illumination of all of the display pixels or may be operated in continuous (cw) mode, using color filters on the display, phase plates (147) or microlens arrays to image light spots (148) of each color only on designated pixels. Two sets of laser sources (123), either orthogonally linearly polarized or at slight different wavelengths, can be used to create 3-D images. Each set may illuminate a different display panel, one for each eye, or the two sets may be time multiplexed using the same display panel (125). A viewer has polarizing or bandpass filters in front of each eye to separate the binocular images. Fiberoptic coupling (99) of the laser sources (81, 83, 85, 87) can be used to physically separate these sources and their power supply from the display panel (115).

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Description

Laser Illuminated Display System

Technical Field

The present invention relates to optical systems involving optical spatial modulators, such as liquid crystal or micromirror array display panels, and in particular relates to efficient illumination of such panels.

Background Art

Optical spatial modulators using liquid crystal material or deformable micromirrors have found application as flat panel displays in portable or notebook computers, and are being seriously explored for use in head-mounted display virtual-reality systems, in high-definition projection television systems and in digital motion picture theatre projection systems. Monochrome and color liquid crystal display panels are commercially available and improvements based on active matrix and other technologies are presently being developed. A survey of the present display technology and the development efforts is presented by Kenneth Warner in IEEE Spectrum, November 1993, on pages 18-26 in an article entitled "The flat panel's future". The basic illumination for such systems is from a fluorescent lamp passing light through a diffuser and linear polarizer onto the liquid crystal display panel. For color displays, the panel includes red, green and blue filters corresponding to display pixels. While the electrical-to-optical efficiency of a fluorescent lamp is generally high (over 50%), significant optical losses between the lamp and the display panel, including unused back or side directed light, polarization losses of at least 50% and the unused wavelengths of the broad spectrum fluorescent lamp lost at the color filters, the overall efficiency is very low. Further losses occur from illumination of the interpixel areas of the

display panel which contain control and pixel driver electronics.

Catoptric collection systems to redirect the backwards propagating light forward make the illumination optics much more complicated and make the already cumbersome head-mounted systems under development even heavier.

Another display technology which is currently available from Texas Instruments Inc. is digital micromirror devices. The devices use a matrix of deformable silicon micromirrors which can be oriented by control electronics in either of two directions. Light that illuminates the micromirrors is either reflected through a projection lens onto a view screen or misses the projection lens aperture and is trapped, depending on the tilt of the individual mirrors. Color systems use a rotating color wheel inserted into the light path and synchronized to the system electronics. A survey of this micromirror technology is presented by Jack Younse in IEEE Spectrum, November 1993, on pages 27-31 in an article entitled "Mirrors on a chip". Again the illumination system includes a broad spectrum light source, color wheel, and projection lens leading to optical losses between the source and display. However, since this display is polarization insensitive, polarization losses are eliminated.

Other display systems are illuminated by red and green LEDs behind every pixel and a blue color emitting fluorescent lamp illuminating all of the blue pixels, as described in U.S. Pat. No. 5,164,715 to Kashiwahara et al. Sequential illumination of display pixels by scanning laser beams is described in U.S. Pat. No. 4,978,202 to Yang, and in U.S. Pat. No. 5,018,007 to Lang et al. In the latter patent, a sheet of fiber optic cables that have been treated to emit light transversely overlie the display screen and a scanning laser sequentially transmits light to the optical fibers to illuminate one row of pixels after another. The liquid crystal

shutters are activated row by row synchronized with the sequential illumination.

An object of the invention is to provide a display system with efficient illumination of the spatial modulator panel.

Disclosure of the Invention

The object is met by a display system which uses lasers to scanlessly illuminate the pixel elements in a spatially modulating display panel, such as a liquid crystal or micromirror array panel. At least three lasers are used, preferably laser-diode-based red, green and blue sources. For the green and blue sources, or any other sources with a wavelength less than about 600 nm, the sources may be frequency doubled laser diodes using optically nonlinear harmonic generators. Alternatively, upconversion fiber lasers could be used. More than three colors may be used for better color control.

Alternatively, at least one laser source used in conjunction with other illumination means can have at least some of the advantages listed from the use of three laser sources.

In some embodiments, the laser sources all illuminate the same pixel elements of the display panel but are sequentially pulsed to provide rapid time multiplexing of the display illumination. This allows a reduction in the number of display pixels by a factor of three in a color display. In other embodiments, the different color laser sources illuminate different sets of pixel elements, either by means of color filters on the display panel itself or by means of phase plates or microlens arrays that form light spots of each color only on designated pixels. Such phase plate or microlens optics can also be used to reduce optical losses by ensuring that interpixel areas of a display panel are not illuminated. In order to create three dimensional images, two sets of laser sources illuminate one or two display panels, the sources being either linearly polarized in orthogonal

directions or at slightly different wavelengths in the two sets, and the viewer has polarizing or bandpass filters in front of each eye to separate the two separately recorded binocular images. Other embodiments are described in the detailed description that follows.

An advantage of laser illumination over the prior lamp-based illumination is that laser-diode-based sources are small and lightweight and produce a beam that can be collected and distributed with simpler and lighter optics. Also, despite the lamp's possibly greater intrinsic efficiency, the laser-diode-based system has a greater overall efficiency because it produces a brighter output and has less overall light loss between the light source and the display. This allows a smaller, lighter weight battery-powered display owing to the reduced heat generation and lower power requirement. Further, use of fiberoptic coupling can physically separate the laser sources and power supply from the display panel for a lighter, less cumbersome, head-mounted display. Further, the ability to modulate each laser source rapidly can reduce the number of display pixels required by a factor of three substantially decreasing the display cost. Still further, the laser source may be polarized leading to a factor of two improvement in efficiency relative to unpolarized sources which illuminate polarization sensitive displays such as liquid crystal displays.

Brief Description of the Drawings

Fig. 1 is a schematic view of a first laser illuminated display system of the present invention.

Figs. 2 and 3 are respective top and side sectional views of a frequency doubled laser light source for use in the present invention with the section taken along the line 3-3 in Fig. 2.

Fig. 4 is a perspective view of a laser diode light source for use in the present invention.

Fig. 5 is a schematic view of a second laser illuminated display system of the present invention.

Fig. 6 is a transparent perspective view of a light dispersing block for use in the laser illuminated display systems of the present invention.

Fig. 7 is a graph of intensity and filter transmissivity versus wavelength for two sets of laser illumination sources and viewer eyepiece filters for a three-dimensional display system of the present invention.

Fig. 8 is a schematic view of a third laser illuminated display system of the present invention.

Figs. 9a and 9b are respective schematic views of a fiber coupled multilaser light source and a time multiplex multilaser illuminated display system of the present invention.

Figs. 10a-c are schematic views of speckle reducing laser light sources for display systems of the present invention.

Fig. 11 is a schematic view of a fifth laser illuminated display system of the present invention.

Figs. 12a and 12b are graphs of light intensity versus time illustrating pulse modulation of three light sources for color balance.

Fig. 13 is a side view of a laser illuminated micromirror display panel in a system of the present invention.

Figs. 14a and 14b are schematic views of two laser illuminated display systems of the present invention for projecting multiple color sources onto different sets of display pixels.

Fig. 15a is a graph of laser source intensity versus wavelength for a set of high brightness illumination sources for the display systems of the present invention.

Fig. 15b is a schematic view of an optical system for combining two source beams into one higher brightness beam.

Fig. 16 is a schematic view of a dual phase plate optical system for use with the display systems of the present invention to source change intensity profiles.

Best Mode of Carrying Out the Invention

With reference to Fig. 1, a display system of the present invention includes one or more spatial light modulators, in this particular embodiment three in number, 11, 13 and 15, such as liquid crystal or micromirror matrix display panels, and at least three laser sources 17, 19 and 21 of different wavelengths or colors, here labeled as red, green and blue. The red laser source 17 typically emits light with a wavelength between 630 and 650 nm. The green laser source 19 typically emits light with a wavelength between 520 and 540 nm. The blue laser source 21 typically emits light with a wavelength between 460 nm and 480 nm. The actual wavelengths selected for each source will depend on the wavelength standard adopted for a particular application, such as for high definition television, digital motion picture theatre projection systems, or virtual reality head-mounted displays.

In the embodiment shown in Fig. 1, the laser sources 17, 19 and 21 are optically coupled to light transmissive fibers, or to bundles of such optical fibers, 23, 25 and 27. Lasers without fibers may also be used. This may be preferred if maintaining polarization is of importance for efficient operation of the display. The fibers may also be chosen to maintain the laser polarization. The output ends of these fibers or fiber bundles 23, 25 and 27 are, in turn, optically coupled to collimating lenses 29, 31 and 33 placed in front of the display panels 11, 13 and 15. In this manner, the laser sources 17, 19 and 21 are capable of scanless illumination of the spatial light modulators 11, 13 and 15. Light transmitted through the spatial light modulators 11, 13 and 15 can be combined into a single color image by a series of dichroic reflectors 35, 37 and 39. In

this example, the reflector 35 reflects the red light image that has been transmitted through display panel 11. The reflector 37 reflects the green light image that has been transmitted through display panel 13 and also transmits the red light image that was reflected by reflector 35. The reflector 39 reflects both the red and green light images received from reflectors 35 and 37 and transmits the blue light image that has been transmitted through display panel 15. Other arrangements for combining the separate images are also possible. The combined color image is then projected through well known lens projection optics 41 to a view screen 43. Other display system embodiments using three or more laser sources to illuminate a single spatial light modulator, rather than three or more distinct modulators 11, 13, and 15, are described below.

With reference to Figs. 2 and 3, the laser sources are typically diode lasers or laser diode arrays. In the case of wavelengths shorter than about 600 nm, the diode lasers that are presently available which can directly emit light of such wavelengths, namely II-VI compound semiconductor lasers, such as MgZnSSe diode lasers, are currently capable of producing less than about 100 mW of optical output. This is acceptable for some applications, such as head-mounted displays, but is insufficient for others, including flat-screen televisions or digital theater projection systems. It is expected that the power output for these and the, as yet experimental, III-V nitride compound semiconductor lasers will increase as the technology develops. However, at present, frequency doubled diode lasers are the laser source of choice for the green and blue wavelengths. Other blue and green sources may include frequency converted lasers that are based on difference frequency mixing (DFM) of diode laser outputs, and upconversion fiber lasers. Frequency doubling waveguides 47, difference frequency mixing (DFM) media, and other nonlinear optical devices capable of producing frequency converted lasers, are collectively

known in the art as optically nonlinear frequency converters. Such devices are known to be useful for shifting the wavelength of the light emitted from a laser, as in the frequency doubled laser 21 in Figs. 2 and 3. Such a frequency doubled laser 21 (or 19) may include a monolithic MOPA array 45 followed by a planar, optically nonlinear waveguide 47, both mounted on heat sink submount 49. MOPA array 45 can have multiple light emitting elements, typically 10 to 20 in number, each of which includes a single spatial mode DBR laser oscillator section 51 followed by a flared amplifier section 53. A collimating lens element 55 may be integrated into the wide output end of each amplifier section 53. The nonlinear waveguide 47 is preferably butted against the output end of the MOPA array 45. The nonlinear optical material 47, e.g. $LiNbO_3$ may be periodically poled, that is, have periodically alternating ferroelectric polarization domains, for phase matching or quasi-phase-matching the fundamental and second harmonic wavelengths of light in order to obtain efficient frequency doubling. Also, the laser oscillators 51 in the MOPA array are preferably constructed so as to oscillate in the TM polarization mode for best frequency doubling efficiency. A MOPA array of 10 elements emitting 920 nm to 960 nm light with a power of one watt per element can produce a frequency doubled output from the nonlinear waveguide 47 of 460 nm to 480 nm blue light with a power of about 100 mW per element, for a total blue light output power of one watt. Likewise, a 10 element MOPA array emitting 1040 nm to 1080 nm light with a power of one watt per element will result in 520 nm to 540 nm green light after frequency doubling with a total power of about one watt.

The blue or green laser output is coupled into an array of optical fibers 57 corresponding in number to the number of lasing elements in the MOPA array 45. Preferably, the optical fibers 57 are butted or lens coupled to the output end of the frequency doubling waveguide 47. The fiber array 57 may be arranged for ease of

alignment on a grooved fiber tray 59 and mounted with the laser source's submount 49 on a heatsink 61. The optical fibers 57 are rearranged at the fiber outputs as a round fiber bundle, typically with a 400 μm diameter and less than 0.4 NA for a 7-fiber array. The overall electrical-to-optical efficiency from the electrical power input to the MOPA array 45 to the optical power output 63 from the end of the fiber bundle is about 15 percent or 30 lumens per watt, with the brightness of the fiber output 63 being on the order of 10^6 lumens/sr$\cdot$cm^2.

Many alternatives to the MOPA frequency doubled array exist. The first is to resonantly frequency double a single MOPA. The concept of resonant cavity doubling is well described in Kozlovsky et al., Appl. Phys. Lett. 56, 2291 (1990). The 1 W MOPAs with collimating optics are now a standard commercial product. This light is injected into the resonant doubler. A feedback loop and a frequency tunable MOPA are used to lock the laser to the resonator frequency for maximum visible wavelength conversion efficiency. A second alternative is to couple a single mode index guided laser, such as the commercially available SDL 5420 laser, to a quasi-phase matched non-linear optical waveguide. This type of waveguide frequency doubler is described in a paper by Van der Poel, 57, 2074, (1990) and Risk, Appl. Phys. Lett. 58, 19 (1991). An array of such devices could also be coupled to an array of quasi-phase matched nonlinear optical waveguides. The visible light output could then be at least partially collimated by a lens array or other optics to achieve uniform illumination of a light modulator array such as a liquid crystal display. The output from such a device would be linearly polarized. Each laser element in the array could be modulated at high speed greater than 1 MHz or all elements could be driven in parallel in either a pulsed or CW mode.

With reference to Fig. 4, the red laser source can be a ten-element phase-locked laser array with an optical power output of about 100 mW per element for a

total output of one watt. Alternatively, a single lasing element with a flared gain region could be used. As seen in Fig. 4, this single lasing element may have an InGaP active quantum well 65 and InGaAsP cladding layers 67 on a GaAs substrate 69. The structure may have a 1 to 5 μm wide single mode waveguide 71 adjacent to one cavity reflector 73 followed by a flared gain section 75 of about 1 mm to 2 mm length terminating in a 100 to 300 μm wide aperture at a second cavity reflector 77. Such a laser produces approximately one watt of optical output at 640 nm in nearly a single transverse mode. Other high power, high brightness, red laser diode sources are known and could be used. These include a multimode broad area laser or arrays of single mode or multimode lasers.

It should be noted that many of the laser sources that have wavelength selective losses within the laser cavity, such as laser-diode-based sources with one or more grating reflectors, can be actively tuned. For example, a MOPA or DBR laser diode can be actively tuned to emit any wavelength within a certain range (typically about 10 nm, but often as much as 30 nm) by adjusting the refractive index in a grating region of such devices via current injection or charge depletion in the grating region. Such active tuning of the wavelength emission of diode-laser-based sources can be used to adjust the color balance of a laser illuminated display system for the best color image. It may also be used to create 3-D images as explained below with reference to Fig. 7.

With reference to Fig. 5, light from red, green, blue and optional infrared laser sources 81, 83, 85 and 87 is coupled into optical fibers or fiber bundles 91, 93, 95 and 97, respectively, which are then combined into a single fiber or a mixed fiber bundle 99. For a head-mounted display system, optical power of 0.1 mW to 10 mW per color is sufficient. The laser sources can thus be laser diodes directly emitting red, green and blue light, or frequency doubled or difference frequency mixed laser diode, for the green and blue light, or up-

conversion lasers, such as thullium (red, green and blue), erbium (green), praseodymium (red or blue) and holmium (green) doped ZBLAN fiber lasers. The light 101 emitted from the output end 100 of the fiber or fiber bundle 99 is incident upon a dichroic beamsplitter 103 that reflects the infrared light from laser source 87 and transmits the visible light from laser sources 81, 83 and 85. The reflected infrared light 105 is imaged by a lens 107 onto an infrared detector 109. The electrical output 110 of the detector 109 can be used to power the electronics of the display panel 115 if the infrared source 87 is operated to supply power to charge a battery, which then powers the display electronics circuit. The infrared source can also be modulated with the digitally encoded display data signal to trigger the electronics to turn pixels on and off. This would eliminate any electrical wires going into the display region. Since the laser sources 81, 83, 85 and 87 are fiber coupled to the display panel 115, they can be located remote from a head-mounted display. The visible light 111 transmitted through the dichroic beamsplitter 103 passes through an optional binary diffusing screen 113 and illuminates a display panel 115. Display panel 115 is a spatial light modulator, such as a liquid crystal or micromirror display, and the spatially modulated light 117 appears after either being transmitted through or being reflected off of the display panel 115. The laser sources 81, 83 and 85 may be pulsed in sequence at a rate of about 200 Hz or greater, with each source illuminating the entire panel 115. The panel electronics change the pixels of the display panel 115 after each laser pulse to create a rapid sequence of monocolor images that are perceived by humans as a full color image. Such sequential pulsing of each lasing color allows a display with three times fewer pixels to be used relative to lamp illuminated displays. Active matrix liquid crystal display panels, especially those using ferroelectric liquid crystal materials, have a sufficiently fast response time for such rapid config-

uring of the display pixels. Alternatively, the visible laser sources 81, 83 and 85 can all operate in a continuous mode and illuminate a color display panel employing color filters behind each pixel.

Two sets of laser sources can illuminate a pair of display panels to create a binocular image. Alternatively, the single fiber or mixed fiber bundle 99 in Fig. 5 can split into two fibers or fiber bundles for illumination of two display panels, like panel 115, one for the left eye and the other for the right eye.

With reference to Fig. 6, one technique of obtaining uniform illumination of a display panel, such as a liquid crystal display 125, by the laser sources 123, uses a transparent material, light guiding, parallelepiped-shaped block 121. The fiber ends of the red, green and blue laser sources 123 are butted to a back surface of the block 121. This back surface is preferably near 100% reflecting, except for light entrance areas coinciding with the fiber ends. The light from the sources 123 is thus admitted into the light dispersing block 121, and travels down the length of the block 121 to its front surface. If the block 121 is long enough, the light will uniformly illuminate the front surface. This light can then directly impinge on the display 115 and the exit surface 124 might be antireflection coated. Preferably, the front surface 124 has about 90% reflectivity. This allows the light to bounce back and forth inside the block 121 to effectively create a longer path parallelepiped thereby increasing the light uniformity impinging on display 115 without requiring a long dispensing block 121. Additionally, the three light sources may each be made up of multiple lasing elements which can be coupled separately via multiple fibers to the back surface of the light dispersing block 121, or a single fiber from each source may be split into multiple fibers by fiber splitters, so that light can enter the block 121 in multiple regions, producing uniform illumination in a shorter distance. The parallel side walls

and sharp corners of a rectangular-shaped block 121 preserve the desired linear polarization of the laser sources 123 for more efficient use of the light by the illuminated liquid crystal display panel 125. That is, in a liquid crystal display 50% of unpolarized light will be lost. Therefore the linearly polarized laser beam aligned with the proper LC display polarization allows nearly 100% of the illumination light to be visible on the display screen.

Another use of the linearly polarized laser illumination is the creation of 3-D displays. Such displays can be made using two sets of linearly polarized laser sources, one set being laterally polarized red, green and blue sources and the other set being vertically polarized red, green and blue sources, so that each color has both laterally polarized and vertically polarized laser sources. These sources are used in conjunction with a polarization insensitive spatial light modulator, such as a micromirror matrix display panel, for example, the deformable silicon-based reflector arrays made by Texas Instruments. The image is viewed through a set of orthogonally linearly polarized glasses. The laser sources are pulsed sequentially at a rate of at least 360 Hz so that each color and polarization is refreshed at a cycle rate of at least 60 Hz, giving each pulse a one-sixth duty factor and at most 2.8 msec pulse length. A typical illumination sequence might be laterally polarized red, laterally polarized green, laterally polarized blue, vertically polarized red, vertically polarized green, vertically polarized blue, etc. or possibly laterally polarized red, vertically polarized red, laterally polarized green, vertically polarized green, laterally polarized blue, vertically polarized blue, etc. Other sequences are also possible. The spatial modulator is reconfigured for each pulse. Because, one eyepiece of the view glasses is laterally polarized and the other is vertically polarized, each eye receives only the light from a particular polarization, and because of the high

pulse repetition rate, the rapid sequence of monocolor images is perceived by the viewer as a color image, so that a slightly different color scene can be sent to each eye. By having separate digital color cameras record an image from separate locations and angles, as if separated by the separation of the human eyes, and by sending this data to the spatial modulator for illumination by each set of linearly polarized laser sources, a true three dimensional image of the scene can be viewed.

With reference to Fig. 7, another method of achieving three-dimensional pictures is similar to the first, but the sets of linearly polarized laser sources are replaced by two sets of lasers operating at slightly different wavelengths. The polarizing glasses are replaced with filters with passbands at different wavelengths. Figs. 7a and 7c show the laser outputs in intensity I versus wavelength λ for the two sets of laser sources. One set of sources (Fig. 7a) produces light, represented by the intensity spikes 131, 133 and 135, at 440 nm (blue), 520 nm (green) and 630 nm (red). The other set of sources (Fig. 7c) produces light, represented by the intensity spikes 137, 139 and 141, at the slightly longer wavelengths 470 nm (blue), 540 nm (green) and 650 nm (red). Alternatively, a single set of wavelength tunable laser sources may be actively tuned in time multiplexed manner to produce the two sets of emission wavelengths. Figs. 7b and 7d show the filter bandpasses in transmissivity T versus wavelength λ for the two eyepieces of the viewing glasses. One eyepiece (Fig. 7b) has bandpass wavelengths, represented by the transmissivity envelopes 132, 134 and 136, coinciding with the 440 nm, 520 nm and 630 nm intensity spikes of the first set of laser sources and generally blocking transmission of the wavelengths from the other set of sources. The other eyepiece (Fig. 7d) has bandpass wavelengths, represented by the transmissivity envelopes 138, 140 and 142, coinciding with the 470 nm, 540 nm and 650 nm intensity spikes of the second set of laser sources and generally

blocking transmission of the wavelengths of the first set of sources. The cameras recording the image data for use in controlling the spatial modulator configurations for each color also need to be equipped with light wavelength filters with transmissivity bandpasses coinciding with Figs. 7b and 7d in order to render the viewed image as true to color as possible. Filters with the necessary characteristics can be made with colored glass or using interference techniques.

A third method of 3-D imaging is to use both wavelength filtering and linear polarization filtering. This may be required in cases where a particular laser source is not readily linearly polarized or if a particular wavelength laser or filter cannot be fabricated in a cost effective manner.

With reference to Fig. 8, in another embodiment, a single spatial mode laser 143 emits light 144 which is collected and collimated by a lens 145. The light 144 then illuminates a first phase plate 147. The phase plate 147 is constructed so that light transmitted therethrough interferes so as to form, after propagating a certain distance, a periodic two-dimensional array of light spots 148. A spatial modulator 149 having a periodicity matching the spacing of the light spots 148 is positioned at the location of the array of light spots 148. Typically, spatial light modulators, such as liquid crystal arrays have large areas between the pixels 150 occupied by drive electronics where light is not transmitted. If a liquid crystal display panel is directly illuminated with a collimated beam, that portion of the light that falls on interpixel areas is wasted. In this embodiment, all or most of the light is constructed by the phase plate 147 to fall as spots 148 on the pixel areas and thus the light spots 148 are fully transmitted through the display elements 150. As an option, a second phase plate 151 is positioned to reshape the light that is transmitted through the liquid crystal array 149 into

a single collimated beam. Projection optics 152 image the light onto a view screen.

With reference to Figs. 9a and 9b, multiple laser light sources may be used. In Fig. 9a, N laser sources 155-157 are coupled to a number of optical fibers 158-160. At the output end 161 of these fibers, the fibers are arranged in a matrix or other bundle configuration to produce a single high power output beam. An advantage of this scheme is that similar laser sources can be used for both relatively low power applications, such as head-mounted displays or home television projection systems, as well as for relatively high power applications, such as theatre projection systems, simply by scaling the number of laser sources to obtain the required optical power. Note that multiple laser sources without fibers can also be used. These may be lensed to achieve uniform display illumination while maintaining linear polarization.

In Fig. 9b, multiple laser sources are time multiplexed to reduce power requirements and simplify control of the spatially modulating display panels. In this example, four laser sources (including fiber coupling) 163-166 are arranged to illuminate different portions 169-172 of a display panel 168. A lens 167 images the laser light onto the display 168. By pulsing each of the lasers 163-168 sequentially at different time intervals, only a quarter of the display panel 168 is illuminated at each time. Therefore only a quarter of the display panel 168 need be addressed at each time.

Use of multiple, spatially incoherent, laser emitters and other techniques can reduce speckle. Speckle is an effect, related to the coherence of the laser light, which causes unwanted graininess in the image. In the multiple laser embodiment in Fig. 9a, the light from the optical fiber outputs 161 are all incoherent with respect to each other. Since each of the laser sources 155-157 produces its own speckle pattern,

the speckle in the overall image will be reduced as the multiple speckle patterns average out with each other.

In Fig. 10a, light 175 from a laser source is injected into a multimode optical fiber 176, which is tightly looped around a vibrating mechanical transducer 177, such as a piezoelectric crystal or a small loudspeaker-type magnetic transducer. The vibrating transducer 177 stresses the multimode fiber 176 so as to scramble the optical modes of the light 175 propagating in the fiber 176. This results in a smearing of the speckle pattern observed at the output 178 of the fiber. The vibration rate is preferably much faster than display frame rate. The speckle pattern changes faster than the human eye and visual cortex can respond, so the speckle is averaged out.

In Fig. 10b, light 181 from a single spatial mode laser 180 is coupled into an array of fibers 182, which forms a fiber bundle at the output 183. Each of the fibers 182 in the bundle will illuminate a display panel at a different position and will cause different speckle patterns in the image formed on a view screen. Averaging of the different speckle patterns will reduce the total speckle in the viewed image.

Also in Fig. 10b, if the fibers 182 in the bundle have different lengths, and the difference in the lengths of the fibers 182 is longer than the coherence length of the light 181 from the laser source 180, then even if the single light source 180 illuminates the inputs of the fibers 182 with a spatially coherent beam 181, the light at the output 183 of the fiber bundle will no longer be spatially coherent. Each fiber 182 in the bundle will emit light with a different speckle pattern and the overall speckle in the display image will be reduced through the averaging of the different speckle patterns.

With reference to Fig. 10c, a plurality of laser sources 185, each with a slightly different wavelength are coupled into a plurality of optical fibers 187 which

are gathered together into a fiber bundle 189. This results in an output beam 190 with an overall spectrum for each primary color which is broadened relative to the spectrum from any one laser source 185. The width of the spectrum results in reduced coherence length for the light 190, and thus speckle, which depends on the coherence of the source, is reduced in the final display image. The wider the spectrum of the light 190, the less speckle will be generated, because the light no longer interferes coherently. Another way to produce a wider spectrum, although generally not as broad as the multiple source approach shown in Fig. 10c, is to pulse the laser diode. Laser pulsing causes multiple wavelength emission from the laser diode which reduces speckle. The effect can be enhanced by coupling the pulsed light into a glass waveguide with relatively high dispersion. This causes light of slightly different wavelengths to have slightly different optical path lengths. The longer the waveguide is and greater the dispersion, the greater the variation in path lengths and the less speckle that will result. Waveguides, such as the parallelepiped shown in Fig. 6, wherein the light makes multiple passes between the walls and mirrors will also greatly reduce the speckle.

With reference to Fig. 11, a laser source 191 emits light 192, which can be either single or multi-spatial mode light, that is semicollimated by a lens 193. The collimated light 194 illuminates a liquid crystal array 196 through a microlens array 195. The purpose of the lens array 195 is to improve the transmission of light 194 through the liquid crystal array 196 by reducing the amount of light which is incident upon and absorbed by area between the liquid crystal pixel elements in the array 196. For this purpose, the microlens array 195 has a periodic spacing of microlens elements which matches the periodicity of the liquid crystal array's pixels. Each lens element is positioned in front of one liquid crystal pixel element at about a focal length distant. Use of light 194 which has been at least partially

collimated in the most highly divergent transverse dimension by the lens 193, greatly reduces the numerical aperture requirements of the microlens array 195 and improves the collection efficiency of the microlenses. A second lens array 197, substantially matching the first lens array 195, is placed on the output side of the liquid crystal array 196 to recollimate the transmitted light. Multiple laser sources at different wavelengths can be combined readily in the collimated beam region 194 by use of dichroic mirrors so that only one display 196 is required if sequenced laser pulsing is used.

With reference to Figs. 12a and 12b, time multiplexing of each laser source makes it possible to adjust color balance in a color display image in either of two ways. In Fig. 12a, the peak power or intensity of each pulse of the red, green and blue sources can be changed to compensate for differences in brightness of the various sources and the sensitivity of the human eye to different wavelengths. Here, the pulse 201 of the red source is given the most power, the pulse 22 of the green source is given less power and the pulse 203 of the blue source is given the least power. These power levels can be adjusted as needed to create the desired color balance. Alternatively, in Fig. 12b, the pulse length t_1, t_2 or t_3, for each wavelength or color of light is adjusted to create color balance. Here, for example, the green pulse 205 is given a greater pulse length t_2 than the red or blue pulse 204 and 206. The overall combined repetition rate for all three colors remains at 60 Hz or greater to avoid flicker, but the duty factor is increased or decreased to give one or another color more or less relative duration for its pulses. Color balancing can also be achieved by active tuning of one or more laser wavelengths. This wavelength tuning can also be combined with the peak power or pulse width adjustment described in Fig. 12.

With reference to Fig. 13, an incoming collimated beam 210 of light from a plurality of laser sources

illuminates a deflecting micro-mirror-type spatial light modulator 209. This spatial light modulator 209, available commercially from Texas Instruments, has a matrix of deformable silicon micromirrors 211-215, etc. formed on a substrate. Each micromirror represents one pixel and may be deflected or not deflected (or alternatively, deflected in one direction or another). A typical deflection angle is about 10°. The light 210 from the laser sources is reflected from the mirror array 209 and the angle of deflection depends on the orientation of each mirror 211-215, etc. In one deflection position, represented by mirrors 211, 213 and 215, the light 216 reflected by the mirrors is transmitted through a projection lens 217. In the other deflection position, represented by mirrors 212 and 214, the light 218 reflected from the mirrors misses the projection lens 217 and is lost. By using laser sources to produce the collimated beam 210, rather than incoherent light sources, the angle of the incident light 210 is much better defined and the required change in angle of the mirrors 211-215, etc. for projection or loss of the reflected light 216 and 218 is reduced. In addition, contrast of the system is improved. Further, a narrow spatial filter may be used before the projection lens 217 to further take advantage of the high directionality of the laser beam 216.

With reference to Figs. 14a and 14b, phase plates may be used to locate red, green and blue light spots on designated pixels of a display panel to produce a color image without an array of individual color filters on the display panel itself. In Fig. 14a, shown with just two of the colors for simplicity, red and blue laser sources 221 and 222, such as the output ends of laser diode coupled fibers or fiber bundles, provide light to a collimating lens 223. The sources 221 and 222 are differently positioned relative to the optical axis of the lens 223, and so the lens 223 creates collimated beams 224 and 225 with different beam directions for each color. The collimated beams 224 and 225 are directed

onto a phase plate 226. An array of light spots 227 is created by the phase plate 226, where the red and blue spots have the same periodicity but are spatially separated from each other. Each light spot 227 is modulated by a single element of the liquid crystal array 228. A second phase plate 229 on the output side of the liquid crystal array 228 recollimates the light transmitted through the array 228 to form a color image.

In Fig. 14b, phase plates 226 and 229 are replaced by lens arrays 235 and 236. Light coming from sources 231 and 232 is directed as collimated beams in different directions. Light incident on the lens array 235 at different angles are focused by the lens elements onto different pixels of the display panel 234. The light transmitted by the display panel elements is recollimated as a color image by the lens array 236.

With reference to Figs. 15a and 15b, the output power from a laser-based light source can be increased by combining the light from many individual lasers. Typically, the many light sources will increase the total numerical aperture of the combined light source. Therefore, the brightness of the combined light source remains constant when more laser beams are added. However, by combining the light from laser sources of slightly different wavelengths, the intensity of the combined beam can be increased above the level of individual beams. In Fig. 15b, light of a first wavelength λ_1, is combined with light of a second wavelength, λ_2 by means of a dichroic filter 246. The spectrum resulting from combining four sources for each of the blue 241, green 243 and red 245 color sets is shown in Fig. 15a.

With reference to Fig. 16, the intensity profile 253 of a typical laser beam 251 is not optimally matched to the size of a typical display screen. A laser beam 251 typically has a Gaussian type intensity distribution 253 with a certain aspect ratio. The display, on the other hand, is rectangular and a uniform illumination is required. By overfilling the display with light from

the laser, the central, more uniform part of the laser beam may be used. However, this leads to large losses from discarding the non-uniform edge portions of the beam. In Fig. 16, two phase plates 252 and 254 are used to create a uniform light intensity distribution 256 which is matched to the size of the display. Light 251 from the laser is dispersed and collimated by the two phase plates 252 and 254 to change the intensity distribution from the Gaussian profile 253 of the input beam 251 to a uniform distribution 256 for the output beam 255. This approach can also be used in combination with the phase plate of Fig. 8 that was used to create many light spots in front of the liquid crystal display. In this case, all of the light spots will have uniform intensity.

Claims

1. A display system comprising

a spatial light modulator having a plurality of pixels,

at least three laser sources of different wavelengths, each source positioned for scanless illumination at a given time of pixels of said spatial light modulator that correspond at that time to the wavelength of that source, and

means disposed between said laser sources and said spatial light modulator for dispersing light from said sources uniformly onto said illuminated pixels.

2. The display system of claim 1 wherein each pixel of said spatial light modulator corresponds sequentially to each of said wavelengths and said laser sources are pulsed in sequence for time multiplexed scanless illumination by each successive source of all of said pixels of said spatial light modulator.

3. The display system of claim 1 wherein each pixel of said spatial light modulator is dedicated to a particular wavelength and said laser sources are operated in a continuous mode, each laser source illuminating only a designated subset of pixels of said spatial light modulator consisting of all pixels dedicated to the particular wavelength emitted from that laser source.

4. The display system of claim 3 wherein a phase plate is disposed between said laser sources and said spatial light modulator, said phase plate forming light spots on each said designated subset of pixels of corresponding wavelength.

5. The display system of claim 3 wherein a microlens array is disposed in front of groups of pixels of said spatial light modulator, light from said sources being imaged by said microlens array onto said designated subset of pixels of corresponding wavelength.

6. The display system of claim 1 wherein a phase plate is disposed between said laser sources and said spatial light modulator, said phase plate forming light spots on each pixel of said spatial light modulator.

7. The display system of claim 1 wherein a microlens array is disposed in front of said spatial light modulator, said microlens array and spatial light modulator having matching spatial periodicity.

8. The display system of claim 1 wherein said means for dispersing comprises a transparent, light guiding, parallelepiped-shaped block with reflective front and back surfaces, light from said sources being coupled into said block through said back surface and coupled out of said block to uniformly illuminate said spatial light modulator through said front surface.

9. The display system of claim 1 wherein said laser sources comprise laser diodes.

10. The display system of claim 1 wherein at least two of said laser sources are wavelength tunable.

11. The display system of claim 1 wherein each laser source has an adjustable pulse duty factor.

12. The display system of claim 1 wherein there are two sets of at least three laser sources each, said two sets of sources having different sets of light emission wavelengths.

13. The display system of claim 1 wherein said spatial light modulator is a liquid crystal display panel.

14. The display system of claim 1 wherein said spatial light modulator is an array of deflectable micromirrors on a monolithic substrate.

15. The display system of claim 1 wherein each laser source comprises a plurality of laser emitters, said laser emitters emitting light which are incoherent with respect to each other, and means for combining light emitted from said laser emitters into a single beam illuminating said spatial light modulator.

FIG. 1

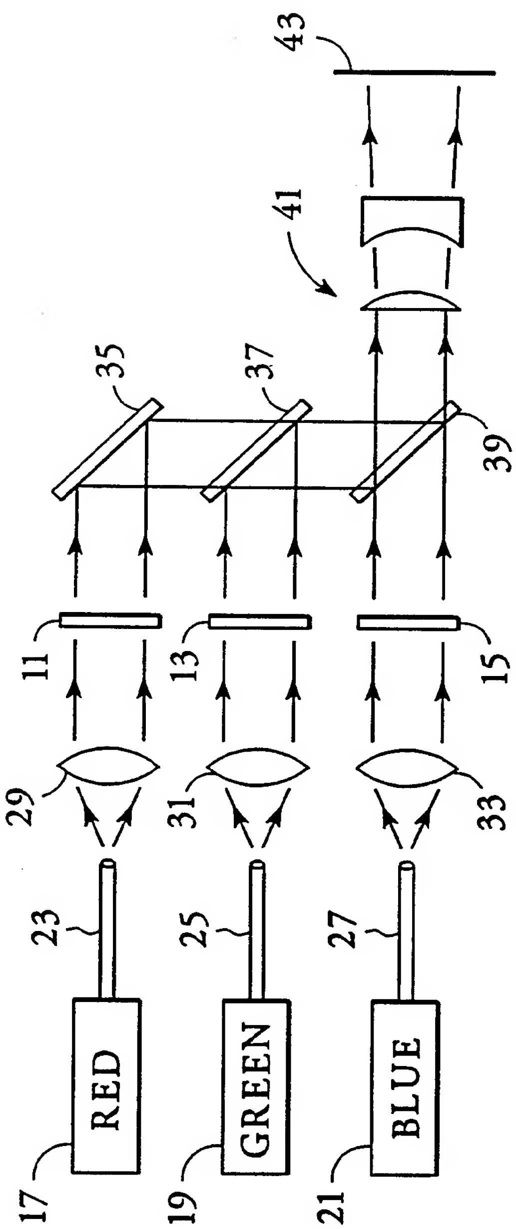
RED
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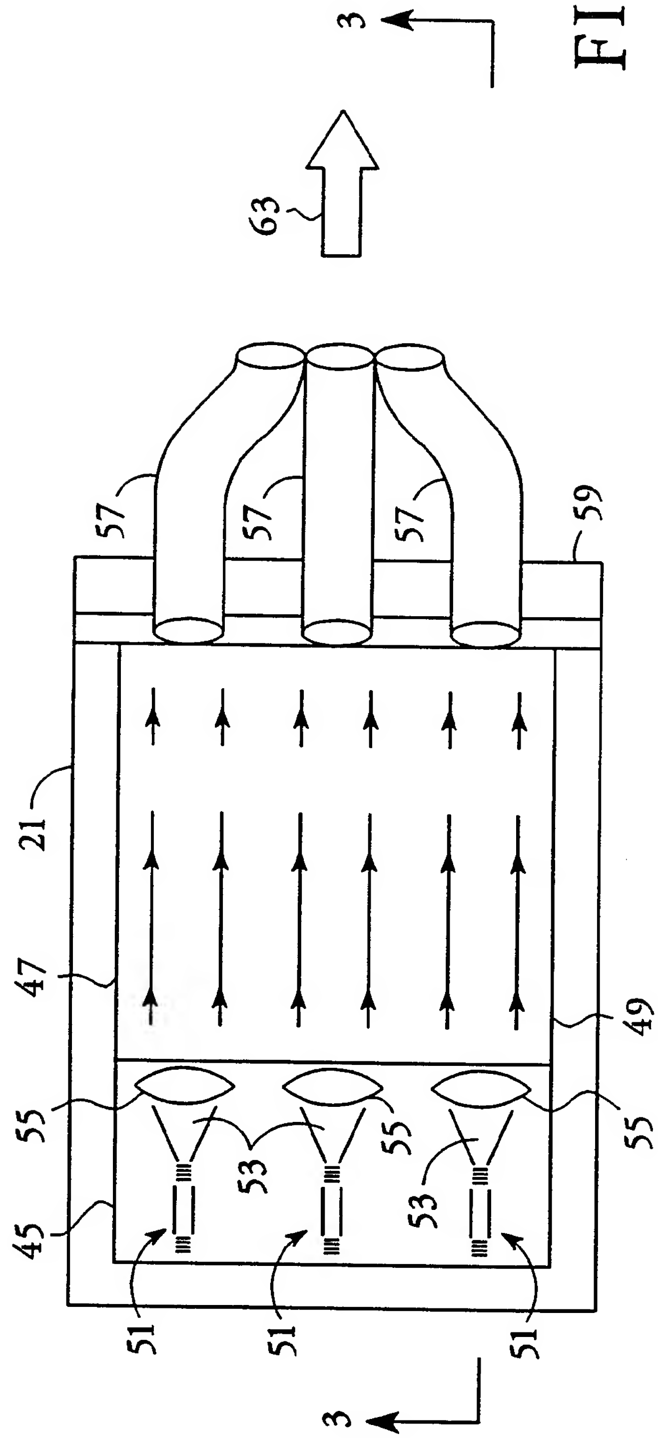
FIG. 2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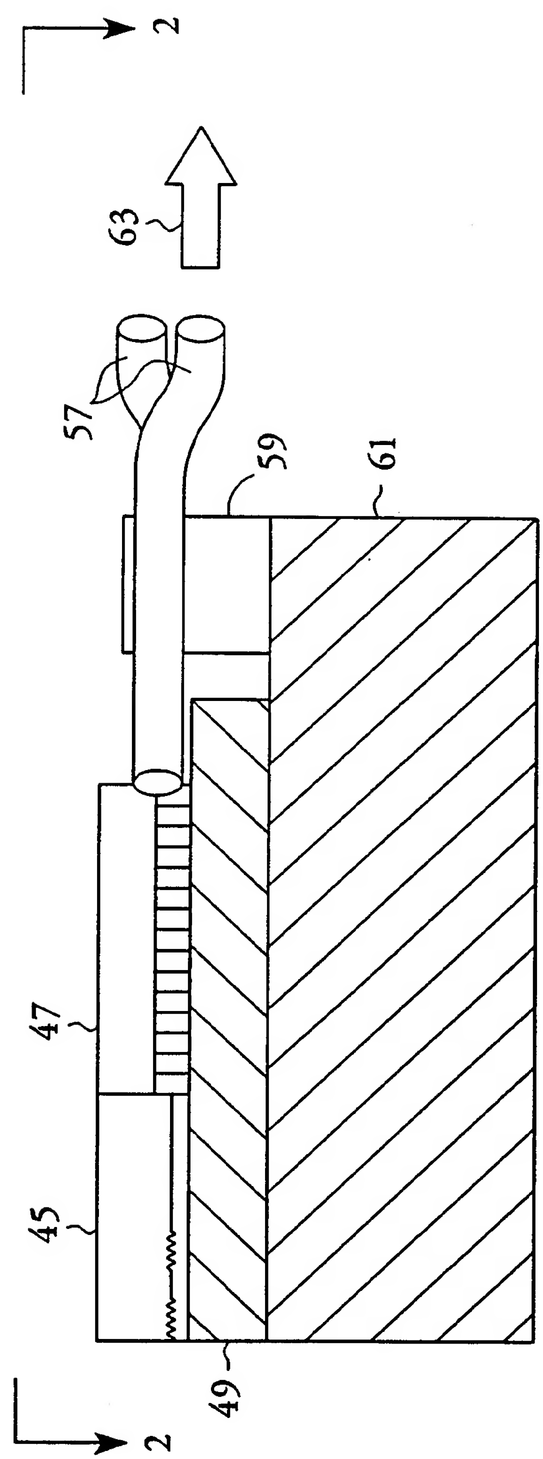


FIG. 3

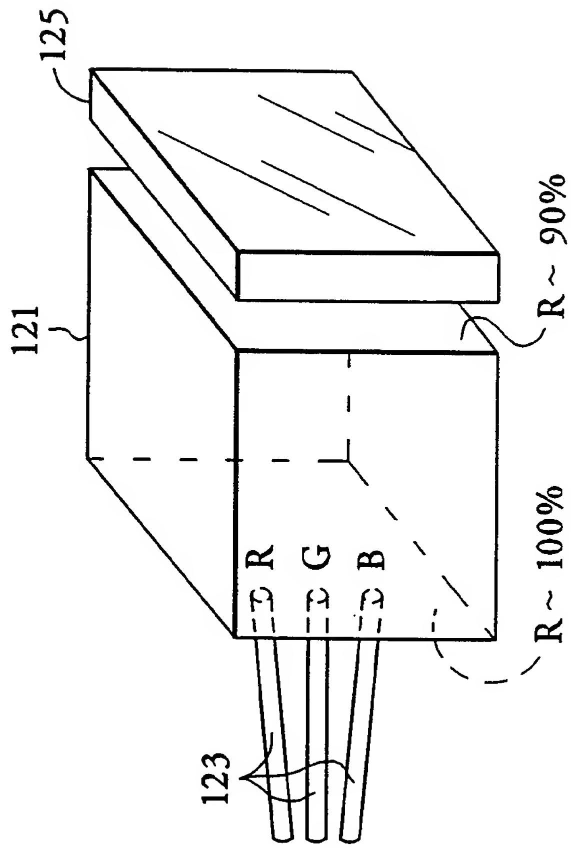


FIG. 6

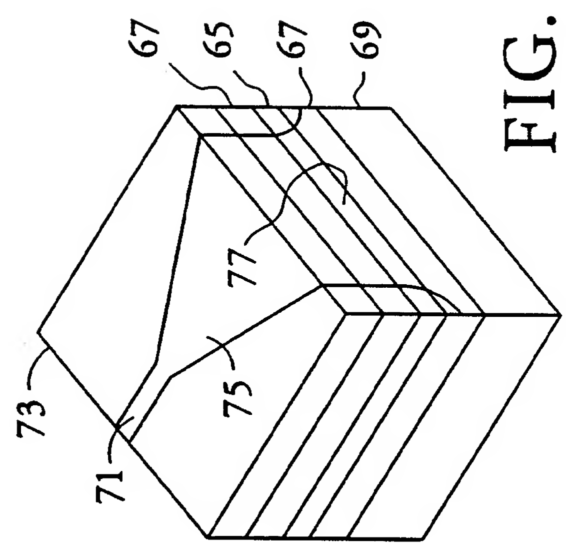
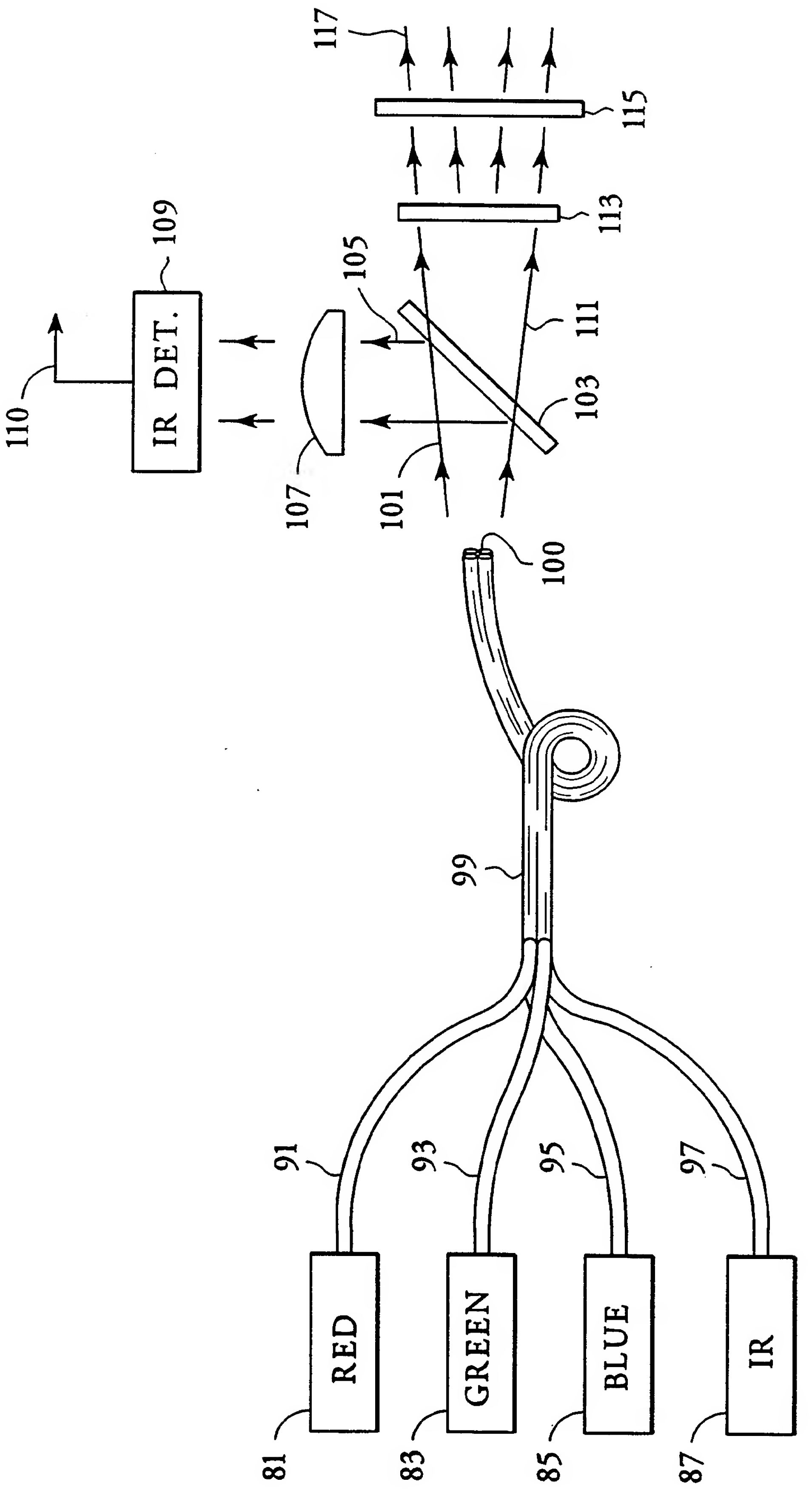


FIG. 4


RED
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IR DET.
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FIG. 5

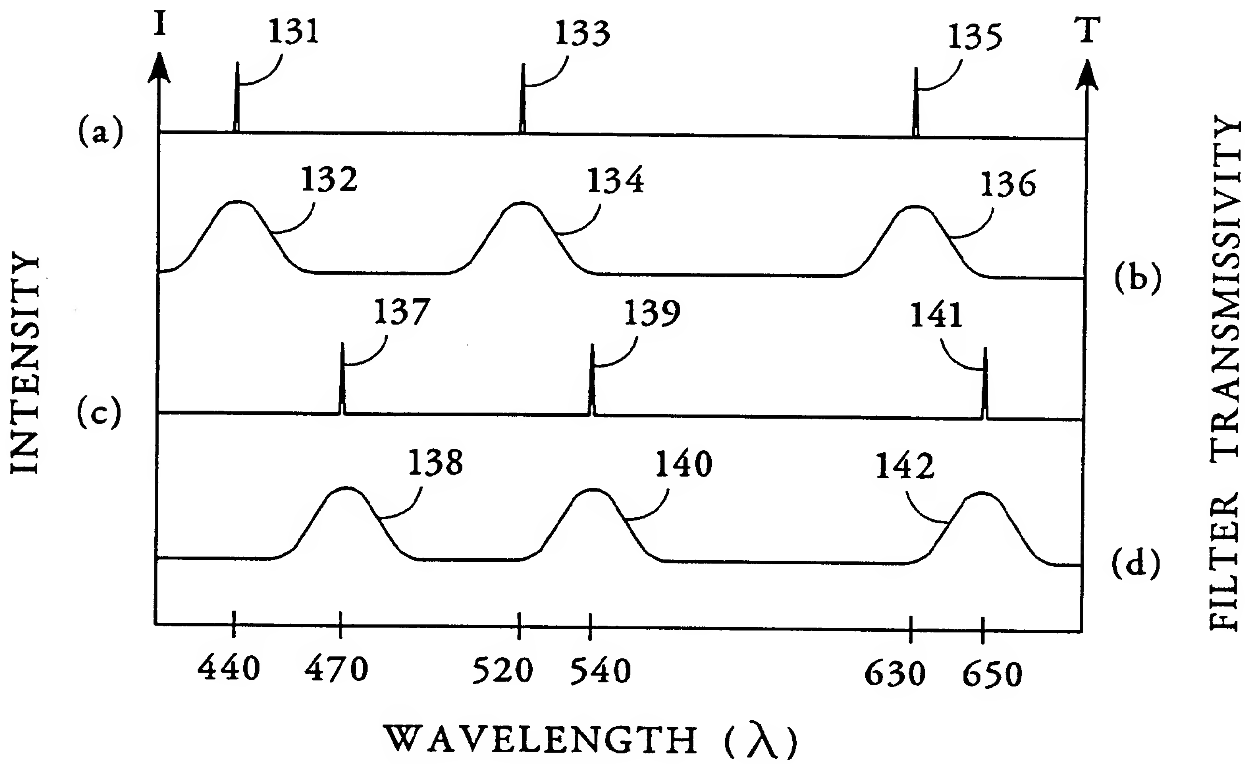
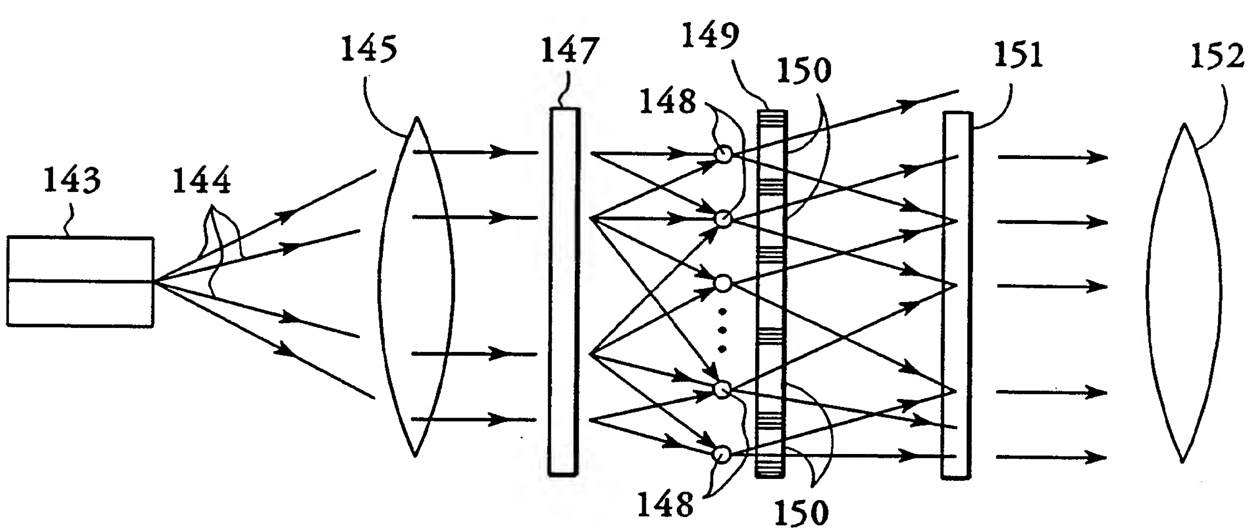

I
T
131
133
135
(a)
132
134
136
(b)
137
139
141
(c)
138
140
142
(d)
INTENSITY
FILTER TRANSMISSIVITY
440
470
520
540
630
650
WAVELENGTH (λ)

FIG. 7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150

FIG. 8

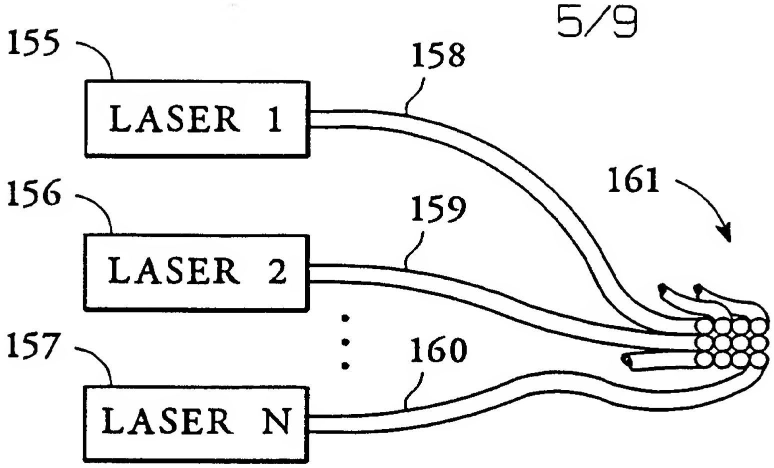

FIG. 9A

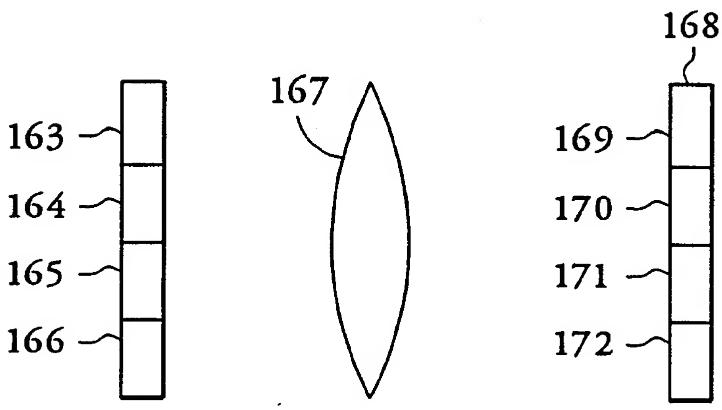

FIG. 9B

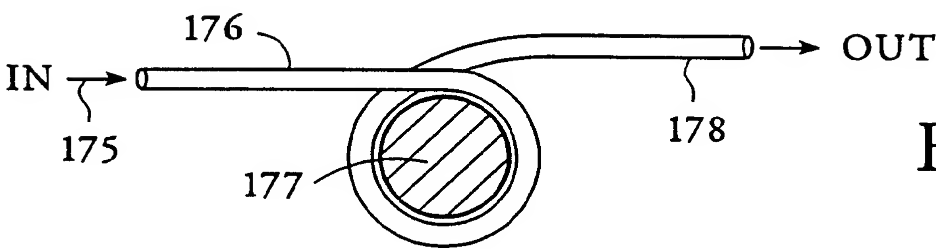

FIG. 10A

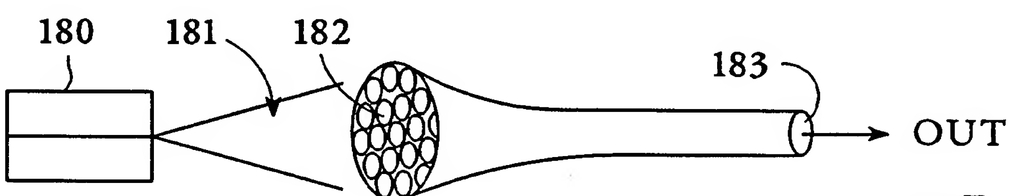

FIG. 10B

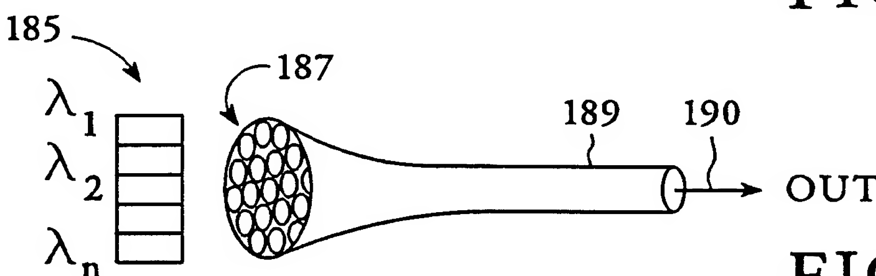

FIG. 10C

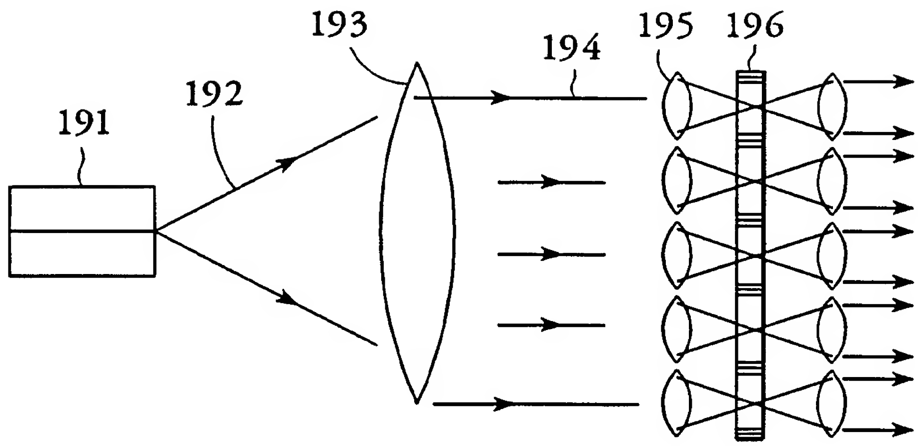

FIG. 11

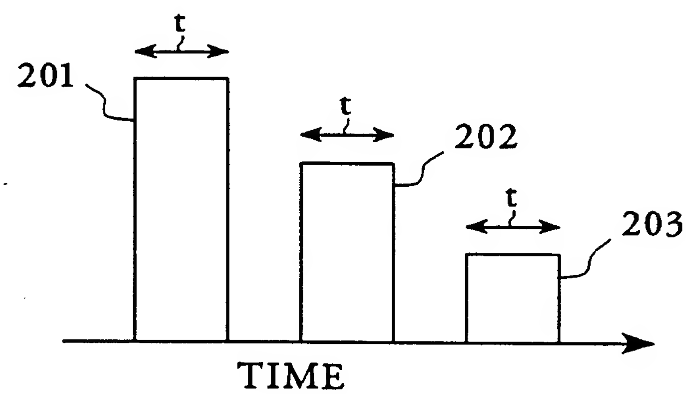

FIG. 12A

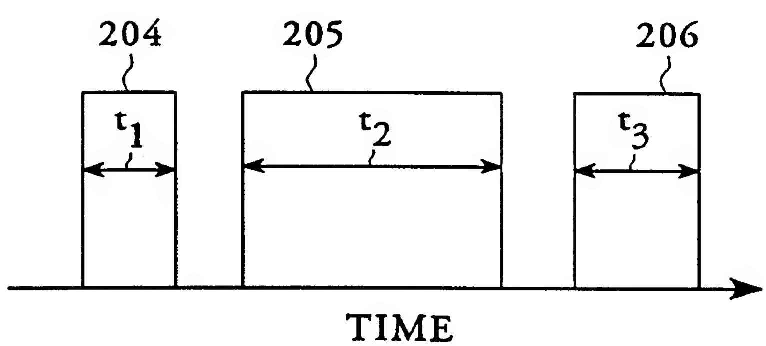

FIG. 12B

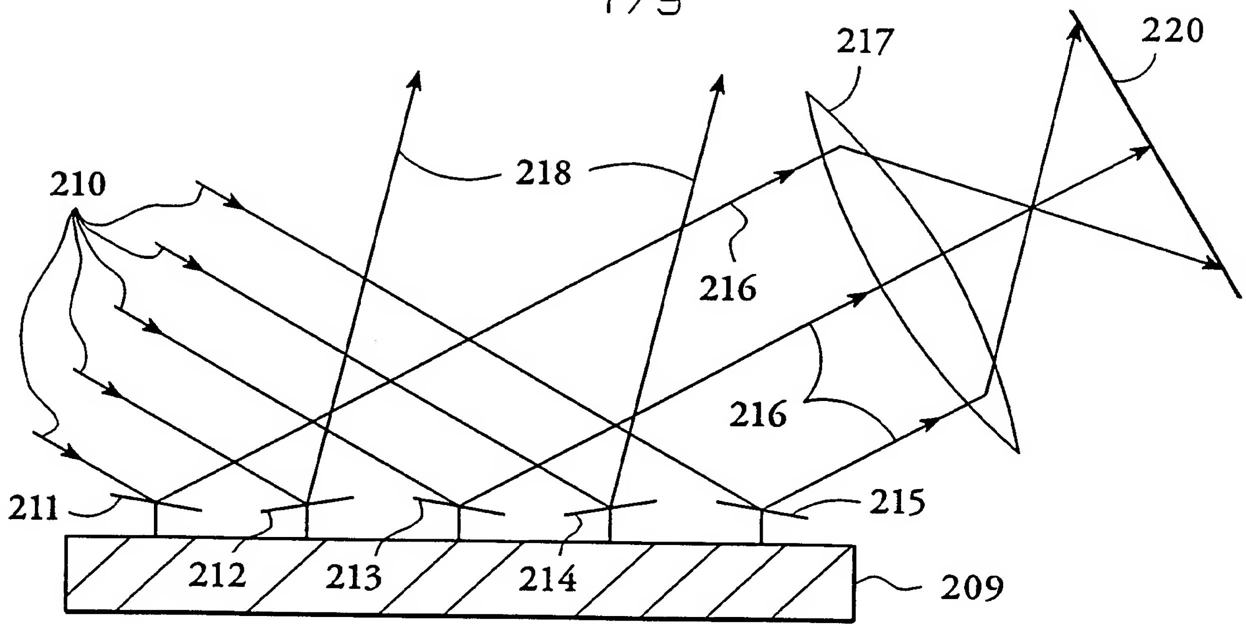

FIG. 13

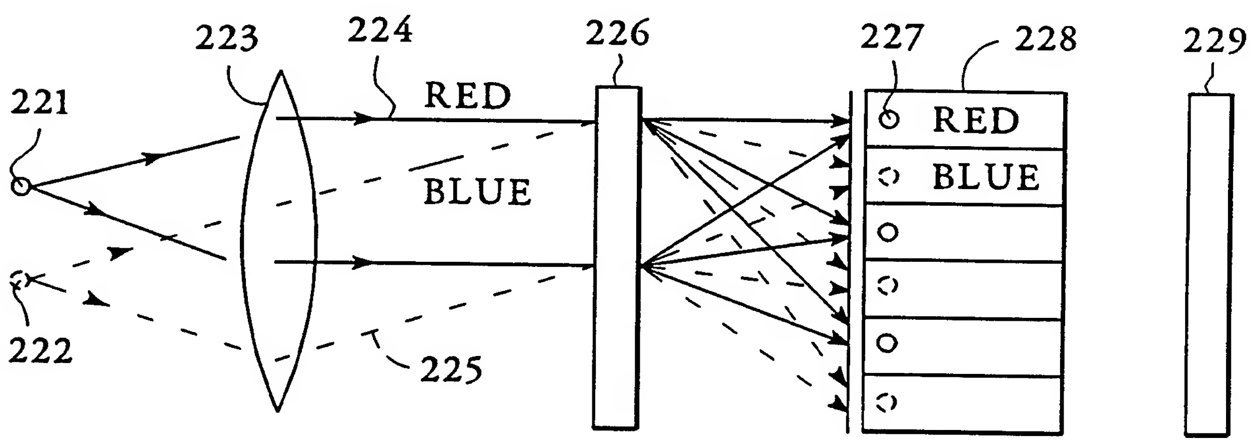

FIG. 14A

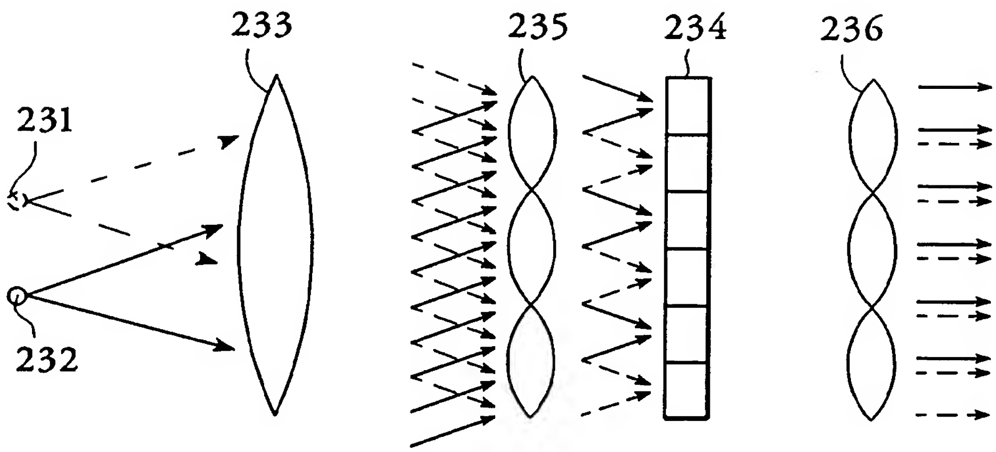

FIG. 14B

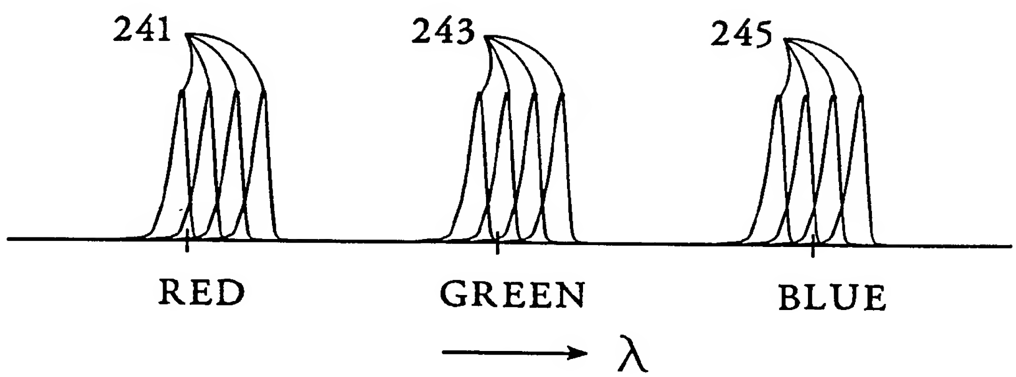

FIG. 15A

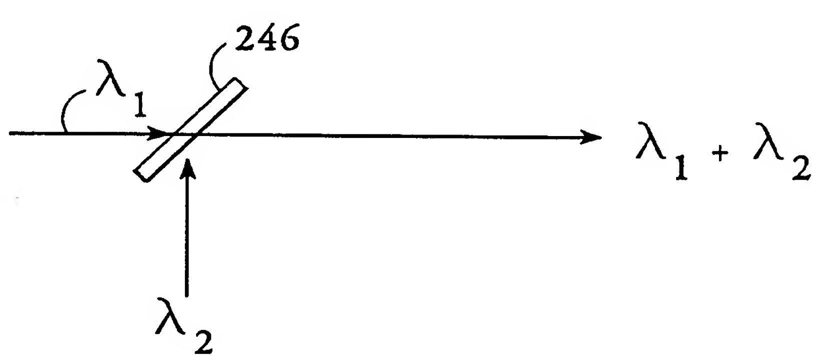

FIG. 15B

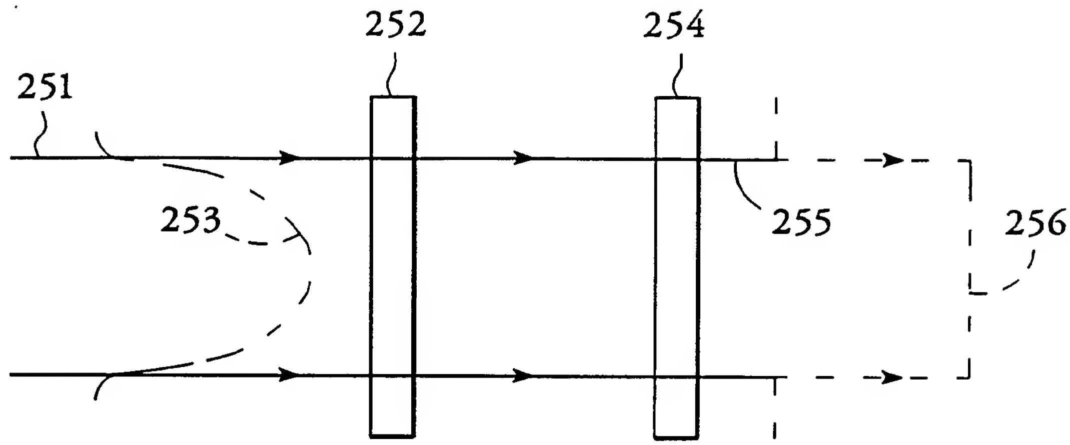

FIG. 16

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US95/00581

A. CLASSIFICATION OF SUBJECT MATTER

IPC(5) : G09G 3/22, 3/28
US CL : 345/32, 87
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 345/32, 87; 349/758, 761

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US, A, 4,978,202 (YANG) 18 December Col. 2, lines 23-54, Col. 4, lines 3-6, and Fig. 1.	1-15
Y	US, A, 4,978,952 (IRWIN) 18 December 1990 Col. 4, lines 20-49, Col. 5, lines 9-14, Col. 8, lines 6-10, Col. 12, lines 41-46, and Fig. 2.	1-15

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be part of particular relevance

"E" earlier document published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search
21 MARCH 1995

Date of mailing of the international search report
03 MAY 1995

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